DIVISION S-6—SOIL & WATER MANAGEMENT & CONSERVATION

Variation of Surface Soil Quality Parameters by Intensive Donkey-Drawn Tillage on Steep Slope

Y. Li, G. Tian,* M. J. Lindstrom, and H. R. Bork

ABSTRACT

Few direct measurements are made to quantify the erosion from upslope to lower field boundaries by intensive tillage. We conducted 50 plowing operations over a 5-d period using a donkey-drawn moldboard-plow on steep backslope in the Chinese Loess Plateau. Topographic changes at different slope positions were quantified using differential global positioning system (DGPS). Soil organic matter (SOM), extractable P and N, and soil bulk density were measured along a downslope transect after each 10-tillage series. Fifty operations resulted in a decrease in maximum soil surface level (SSL) of 1.25 m in the upper slope position and an increase of 1.33 m at the bottom of the slope. Slope gradients decreased from 37 to 14° at the upper position and from 18 to 0° at the lower position. Surface soil bulk density increased from 1.14 to 1.28 Mg m^{-3} in the upper slope and decreased from 1.10 to 1.03 Mg m^{-3} in the middle slope. Mean SOM concentrations in the upper and middle positions of the slope decreased from 8.3 to 3.6 g kg^{-1}, mineral N from 43.4 to 17.4 mg kg^{-1}, and Olsen-P from 4.5 to 1.0 mg kg^{-1}. Intensive tillage resulted in a short-term increase in SOM and available nutrients in the lower portion during the tillage operations. Geomorphologic evolution and landscape variability of dissected hillslopes are attributable to soil movement and resulting physical and fertility degradation induced by intensive tillage.

Over the last decade, researchers have measured net downslope movement of soil by tillage translocation in a wide range of agricultural landscapes in North America (Lindstrom et al., 1990, 1992; Lobb et al., 1995), Europe (Govers et al., 1994, 1996), and Asia (Turkelboom et al., 1997, 1999; Thapa et al., 1999a, 1999b; Zhang et al., 2001). Significant progress has been made on quantifying relationships between tillage translocation and tillage depth, tillage tools, slope gradient, or slope curvature (Lindstrom et al., 1990, 1992, 2000; Govers et al., 1994; Lobb et al., 1995; Dabney et al., 1999; Montgomery et al., 1999; Quine et al., 1999; Thapa et al., 1999a; Turkelboom et al., 1999; Van Muysen et al., 2000). Although these data are useful for soil erosion modeling, soil conservation planning, and the development of soil conservation practices on cultivated land with complex topography, it does not address variations in surface soil quality as affected by soil redistribution due to tillage within a complex agricultural landscape. Quantitative data on the direct effects on surface soil quality indicators within the tilled layers of sloping land at different spatial and temporal scales are needed to establish a cause–effect relationship between soil redistribution by tillage and soil quality (Lal, 1999; Pennock, 1998).

To assess the effects of tillage-translocated soil on surface soil properties and soil quality within the tilled layers, researchers have used modeling (Schumacher et al., 1999; Lobb and Kachanoski, 1999; Van Oost et al., 2000), physical tracers (Poesen et al., 1997; Thapa et al., 2001), fallout ^{137}Cs technique (Li et al., 2000; Li and Lindstrom, 2001), and long-term field studies (Sibbesen, 1986). These studies are very helpful in demonstrating the potential effects of tillage-translocated soil on surface soil properties and soil quality, but they have limitations because of three reasons. First, bulk soil movement predicted by existing tillage erosion models is not always in agreement with redistribution of soil nutrients (Schumacher et al., 1999; Van Oost et al., 2000). Second, physical tracers widely used in tillage experiments cannot be bound with soil particles and therefore do not adequately describe variations in soil physical and chemical properties with tillage operations (Poesen et al., 1997; Thapa et al., 2001). Third, long-term field investigations do not distinguish between the net effects of tillage erosion from water erosion or other soil management practices (Sibbesen, 1986), similar to fallout ^{137}Cs technique (Li et al., 2000; Li and Lindstrom, 2001).

In our previous studies (Li et al., 2000; Li and Lindstrom, 2001), we indirectly estimated soil redistribution rates from tillage using tillage erosion prediction model (TEP), and then linked them to soil quality parameters (Li and Lindstrom, 2001). The key point for utilization of the TEP is to assign an appropriate *k*-value (the tillage transport coefficient per unit slope gradient) for animal powered tillage, which is affected by many environmental factors (Van Muysen et al., 2000). Moreover, the soil quality parameters measured in our previous

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Abbreviations: DGPS, differential global positioning system; SOM, soil organic matter; SSL, soil surface level; TEP, tillage erosion prediction.

Fig. 1. Tillage experiment plot (20 m by 15.5 m) established on a steep backslope within the Yangjuangou catchment. ○: Soil sampling points, - -►: DGPS measuring points, and ▭: Tracer plot.

studies actually reflected both water and tillage erosion processes. Although intensive tillage operation on steep slopes over the last 50 yr has been considered as the major reason for the accelerated soil erosion in the China's Loess Plateau, its effects on soil quality has never been directly measured (Liu, 1985). In the present study, we measured changes in SSL by using survey-grade DGPS and soil quality parameters by direct sampling of the tilled layer immediately after a series of tillage operations, excluding water erosion. We used the donkey-drawn tillage operations in this study as traditionally, farmers plow their fields annually with an animal-drawn moldboard in the hilly and gully regions of the loess plateau. The objectives were to (i) determine the patterns of topographic evolution of steep hillslopes, (ii) examine the dispersion of SOM and available nutrients within the tilled layer during intensive tillage operations, and (iii) quantify the net effects of intensive tillage on surface soil quality and their variation at different slope positions.

MATERIALS AND METHODS

The Site

The trial was conducted on a steep backslope in the Yangjuangou watershed (36° 42′ N, 109° 31′ E), near Yan'an city, northern Shaanxi province of China. The distinctive characteristics of the landscape at the study site are narrow summits (averaging 30 m) and long linear backslopes (150–300 m). The long steep backslopes have been dissected and managed as several small fields by different landowners since 1982. The soil in study area was developed from Malan loess with uniform soil texture along the profile (16% clay, 50% silt, and 34% sand), and classified as Calciustepts in the U.S. taxonomic classification system (Soil Survey Staff, 1999). Water erosion is a recurring problem and the result of deforestation on steep slopes and the extremely high erodibility of the loess soils (Li, 1995). Pearl millet [*Pennisetum glaucum* (L.) R. Br.] and soybean [*Glycine max* (L.) Merr.] are the major crops in the rotation with potato (*Solanum tuberosum* L.) and corn (*Zea mays* L.) growing in the study area. The site was plowed once a year before the study. The farmers in the region practiced donkey-drawn contour tillage for over 1000 yr.

Experimental Set-Up

The tillage experiment plot was demarcated from the lower boundary of a sloping field (20 by 20 m) of 27° (19–36°) (Fig. 1). Tillage was conducted in August 2001 (Fig. 2). Two skillful farmers and two similar donkeys were selected for the intensive tillage operation. The plot area was tilled along contour to a depth of 15 cm with a 20-cm wide moldboard. To investigate the effects of intensive tillage on soil quality within the plow layer, 50 plowing operations were conducted over a 5-d period. We assumed the 50 operations could be equivalent to

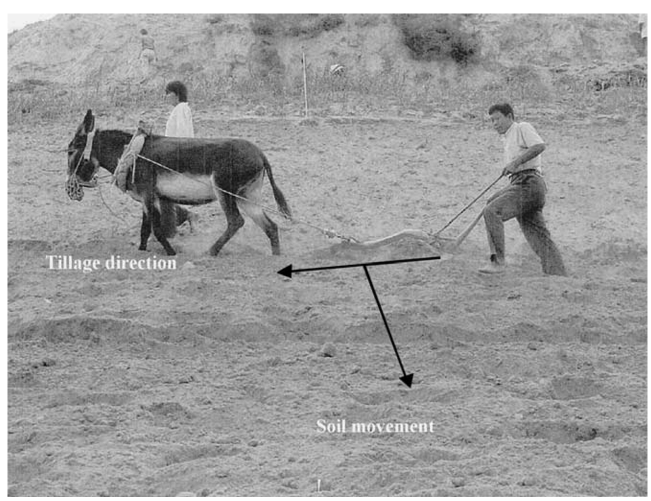

Fig. 2. A donkey-drawn moldboard-plow tillage system used in the tillage experiment.

50 yr of tillage as farmers normally till their land once a year. No rain occurred during tillage operation. For each tillage operation, tillage (plow) started at the lower boundary and worked upslope, turning the soil downslope. Before tillage, topographic data were collected using a DGPS (ProMARK X-CM, Thales Navigation, San Dimas, CA) in 5 by 5 m grids.

Observations and Sampling

Soil Movement Along the Slope

Physical tracers were inserted into the soil at two locations and two depths. Before tillage, two pits of 1.0 by 0.2 m were dug at 30 cm from the upper plot boundary (Fig. 1), and plywood frames were installed. In each pit, 1 kg of red rock fragments was evenly laid at the 15-cm depth. The excavated soil was then returned to the pit and packed to its original bulk density to a depth of 5 cm. At 5 cm of depth, 1 kg of blue rock fragments was added and covered with soil excavated from the depth. Average rock fragments size were 3.5 by 3.5 by 2.0 mm. At the completion of the 50 plowing operations, the tilled soil was sampled in 0.2-m intervals across the entire plot starting from the lower field boundary and moving up to the upper field boundary. Sampling depths were at each 10 cm until where not disturbed by tillage. Rock fragments were collected in a 2-mm sieve, washed, dried, and then weighed. Gross downslope soil movement from the upper field boundary was estimated by the percentage of tracers found at a specific down slope position to the total tracers recovered in whole tilled slope.

Soil Surface Level

This was measured using a DGPS along a downslope transect at various horizontal distances from the upper slope: 0 m (top of slope, TS), 0.4 m (upper slope, US), 2.9 m (midslope, MS1), 5.4 m (midslope, MS2), 10.1 m (midslope, MS3), 12.8 m (lower slope, LS), and 14.7 m (bottom of slope, SB).

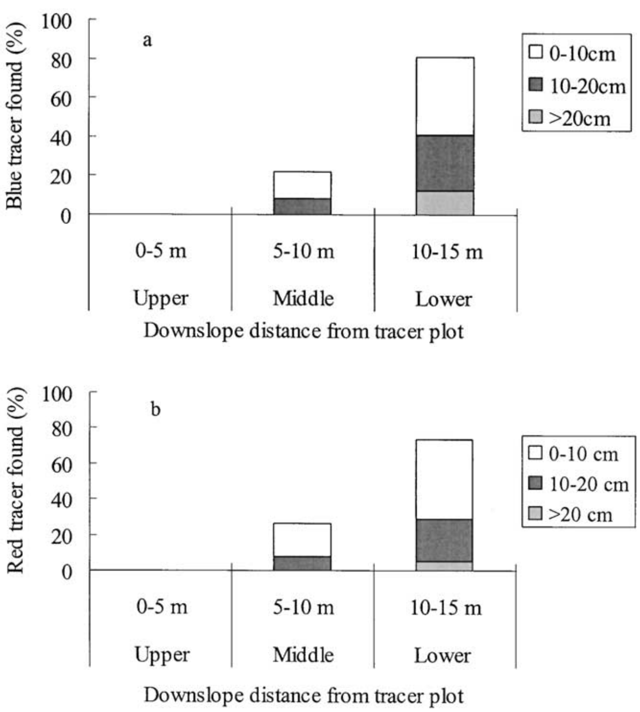

Fig. 3. Recovery of (a) blue and (b) red tracers at different soil depths and locations after 50 tillage operations.

Soil Quality Parameters

Composite soil samples were collected at the upper slope (0.3 m from the upper boundary), midslope (7.5 m from the upper boundary), and lower slope (0.3 m above the lower field boundary). Four sampling points at each slope across the tilled slope were mixed to form a composite sample. The samples were collected using a cylinder of 100 cm^3 to a depth of 15 cm at the completion of each 10 tillage series. The soil samples were air-dried and ground to pass a 0.5-mm sieve for laboratory analysis. Soil bulk density samples were obtained using the core method (Blake and Hartge, 1986) with a metal cylinder of 5 cm (diam.) by 5 cm (length).

Laboratory Analyses

Soil organic matter was measured by the wet combustion method (Nelson and Sommers, 1982). Available soil N was measured by using microdiffusion (Bremner, 1965). Available P was determined using the Olsen method (Olsen and Sommers, 1982).

Data Analysis

Analyses of variance were conducted to test the significance in the variability of SSL and surface soil quality parameters at individual positions of the slope. Regression modeling techniques were used to develop relationship between tillage intensity and the variability of soil quality parameters within the tilled layer. All statistical analyses were performed using Statistical Analysis System (SAS) General Linear Model procedures (SAS Institute, 1990).

RESULTS

Evidence of Soil Movement

Recovery rate of applied tracers was 98% for the blue tracer and 95% for the red tracers (Fig. 3). Seventy-three percent of recovered red tracers was found in lower slope position (10–15 m from tracer plot), 27% in the middle slope position (5–10 m from the tracer plot), and 78% of recovered blue tracers in the lower slope position, 22% in middle slope position. No tracers were found in the upper slope position (0–5 m from tracer plot). The tracer data from Fig. 3 confirmed a significant net soil movement from the upper slope position to the lower slope position.

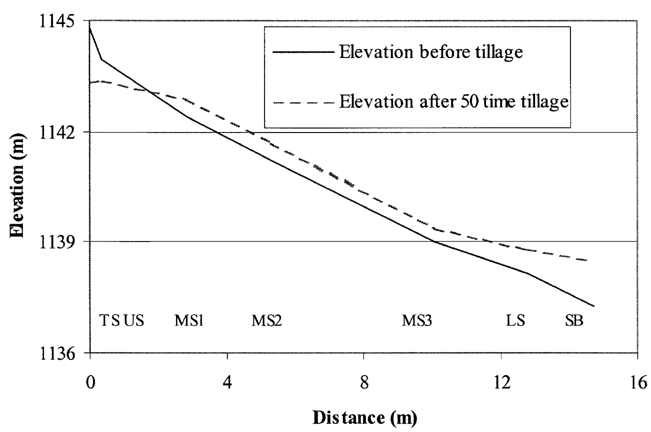

Fig. 4. Change in elevation along the downslope transect after 50 tillage operations.

Table 1. Change in soil surface levels following each 10 tillage operations along downslope transect.

Locations	Horizontal distance from top	Intervals of tillage numbers				
	m	1–10	11–20	21–30	31–40	41–50
Top slope	0.0	−0.57a†	−0.23b	−0.17b	−0.14b	−0.14b
Upper slope	0.4	−0.12a	−0.12a	−0.16b	−0.09a	−0.10a
Middle slope 1	2.9	0.26a	0.14a	0.15a	−0.12b	0.08a
Middle slope 2	5.4	0.24a	0.08b	0.08b	0.02b	0.09b
Middle slope 3	10.1	0.03a	0.08a	0.03a	0.09a	0.14b
Lower slope	12.8	0.04a	0.06a	0.06a	0.19a	0.31b
Slope bottom	14.7	0.55a	0.23b	0.16b	0.20b	0.19b

† Figures followed by the same letters within a row are not significantly different at $P = 0.05$.

Table 2. Relationships between cumulative changes in soil surface level (y) calculated by addition of intervals in Table 1 and tillage operation numbers (x) along a downslope transect.

Location	Horizontal distance from top	Regression equation	R^2	n	P
	m				
Top slope	0.0	$y = -0.017x - 0.439$	0.99	5	<0.001
Upper slope	0.4	$y = -0.012x - 0.011$	0.99	5	<0.001
Middle slope 1	2.9	$y = 0.005x + 0.271$	0.56	5	NS†
Middle slope 2	5.4	$y = 0.006x + 0.186$	0.97	5	<0.001
Middle slope 3	10.1	$y = 0.008x - 0.064$	0.95	5	<0.01
Lower slope	12.8	$y = 0.015x - 0.185$	0.88	5	<0.05
Slope bottom	14.7	$y = 0.019x + 0.732$	1.00	5	<0.001

† Not significant.

Change in Soil Surface Level

Soil surface level decreased significantly in top and upper slopes, and increased in lower slope and slope bottom by tillage operations (Fig. 4 and Table 1). A relatively uniform increase in SSL was found midslope 1 through 3 positions (horizontal distance 2.9–10.1 m). Soil redistribution after 50-tillage operations resulted in a maximum SSL decrease of 1.25 m at the top slope position and a maximum SSL increase of 1.33 m in slope bottom position as the addition of SSL in all intervals in Table 1. Slope gradient calculated from SSL decreased from 37 to 18° at the upper slope position and 18° to near 0° at the lower position.

Effects of tillage number on SSL change varied, depending on slope positions (Table 1). In the top slope position, SSL after the first 10 and 20 tillage operations decreased by 0.57 and 0.23 m, respectively. After the next 10 tillage operations (21–30), a further decrease of 0.17 m was observed, and then a stable decrease of 0.14 m for 31 through 50 tillage operations. The SSL changes at the slope bottom position during the 50 tillage operations were essentially the opposite of what occurred at the top slope position. Regression analysis indicated a positive correlation for the lower slope positions and negative correlations for the upper slope positions between changes in SSL and tillage numbers (Table 2).

Table 3. Comparison of changes in soil surface level (SSL) (m) by 50-plowing operations estimated using the tillage erosion prediction model (TEP) in Lindstrom et al. (2000) with direct measurement using differential global positioning system (DGPS).

	Slope position†				
	TS	US	MS	LS	SB
TEP‡	−1.15	−0.31	0.24	0.44	0.74
DGPS	−1.25	−0.59	0.46	0.66	1.33

† TS, top slope; US, upper slope; MS, middle slope; LS, lower slope; SB, slope bottom.
‡ In the TEP model, k value was set as 250 kg m^{-1} yr^{-1}, and soil bulk density as 1.25 Mg m^{-3} (Li and Lindstrom, 2001).

Change in SSLs with 50-yr tillages calculated using TEP from the topographic data collected before tillage experiment showed a decrease of 1.15 m in top slope position and an increase of 0.74 m in slope bottom (Table 3). There was less difference in SSL changes in top slope between two TEP and DGPS methods compared with that in slope bottom.

Change in Soil Bulk Density

Tillage affected soil bulk density differently at different slope positions (Fig. 5). In the upper portion of the slope, soil bulk density within the 0- to 15-cm depth increased with the increase in tillage number up to 30 tillage operations. Bulk density increased by 12.3%

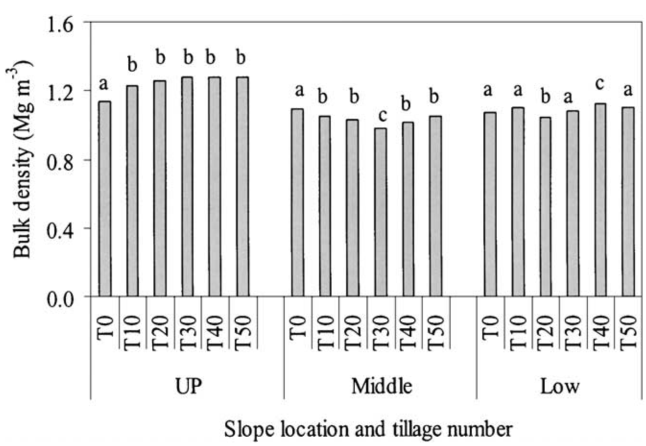

Fig. 5. Surface soil bulk density along a downslope transect, as affected by number of tillage operations. Number following the capital letter T refers to the number of tillage operations. The columns carrying the same letter are not significantly different at $P = 0.05$.

Table 4. Effect of intensive tillage on soil quality parameters at different slope locations.

		Tillage numbers					
Variables		0	10	20	30	40	50
SOM, g kg^{-1}	Upper	8.5a†	4.0b	3.7b	3.8b	3.5b	3.4b
	Middle	8.0a	6.3b	4.9b	4.1b	4.2b	3.8b
	Lower	5.3b	6.9a	6.7b	6.6b	5.5b	4.7c
N, mg kg^{-1}	Upper	52.2a	17.4b	17.4b	17.4b	17.4b	17.4b
	Middle	34.7a	34.8a	27.6a	26.1b	26.1b	17.4c
	Lower	26.1c	43.5a	43.5a	34.8b	34.8b	26.1c
P, mg kg^{-1}	Upper	5.0a	2.4b	1.8b	1.5b	1.2b	1.1b
	Middle	3.9a	2.1b	1.3b	0.9b	0.9b	0.9b
	Lower	2.6b	2.8a	2.7b	2.3b	2.0b	1.5c

† Figures followed by the same letters within a row are not significantly different at $P = 0.05$.

Table 5. Mass balances for SOM and available nutrients after each 10-tillage (calculated using concentration in Table 4 and soil bulk density in Fig. 5).

		Tillage numbers					
		10	20	30	40	50	Total
SOM, kg m^{-2}	Upper	−3.3	−0.9	−0.8	−0.6	−0.5	−6.1
	Middle	+1.2	+0.5	+0.3	+0.0	+0.4	+2.4
	Lower	+2.2	+1.0	+0.8	+1.2	+1.3	+6.5
N, g m^{-2}	Upper	−20.5	−3.7	−3.6	−2.6	−2.7	−33.1
	Middle	+6.5	+2.9	+2.2	+0.0	+1.9	+13.4
	Lower	+14.1	+6.6	+4.1	+7.6	+7.2	+39.7
P, g m^{-2}	Upper	−2.0	−0.5	−0.4	−0.2	−0.2	−3.3
	Middle	+0.4	+0.1	+0.1	+0.0	+0.1	+0.7
	Lower	+0.9	+0.4	+0.3	+0.4	+0.4	+2.4

(1.14–1.28 Mg m^{-3}) by 31 to 50 tillage operations as compared with that at the beginning of tillage. In contrast, soil bulk density decreased with the increase in tillage number (up to 30) in the middle slope position. Bulk density was similar or had no evident trend in change in the lower portion of the slope after tillages.

Change in Soil Organic Matter and Available Nutrients

A rapid decline in SOM, available N and P within the tilled layer of 0 to 15 cm was observed in the upper and middle portions of the slope during the initial tillage period (Table 4 and 5). The rate of such declines was faster in the upper than middle slope in terms of available N. The lower portion of the slope had a significant increase in SOM and available N for the first 40 tillage operations. Available P contents increased for the first 20 tillage operations and then began to decline to a level similar to the upper and middle slope positions at the conclusion of the 50 tillage operations. Regression analysis indicated negative linear correlations between soil quality parameters and tillage numbers for most slope positions (Table 6).

Table 6. Relationships between SOM, available N or available P (y) and tillage intensity/number (x) at different slope positions.

Variables		Regression equation	R^2	n	P
SOM, g kg^{-1}	Upper	$y = -0.013x + 4.08$	0.91	5	<0.05
	Middle	$y = -0.057x + 6.38$	0.81	5	<0.05
	Lower	$y = -0.057x + 7.77$	0.87	5	<0.05
N, mg kg^{-1}	Upper	$y = 0.001x + 17.4$	0.61	5	NS†
	Middle	$y = -0.363x + 37.3$	0.86	5	<0.05
P, mg kg^{-1}	Lower	$y = -0.434x + 49.6$	0.89	5	<0.05
	Upper	$y = -0.032x + 2.54$	0.94	5	<0.01
	Middle	$y = -0.027x + 2.02$	0.72	5	NS
	Lower	$y = -0.033x + 3.25$	0.96	5	<0.01

† Not significant.

DISCUSSION

The decrease in SSL in upper slope and increase in the lower slope with 50 plowing operations in the present study provided a direct evidence that the mass movement of soil by intensive tillage modifies landscape of dissected hillslopes. As changes in surface soil level by 50 plowing operations in our study nearly match those estimated by the TEP model for 50-yr tillage, 50-yr animal-drawn tillage may result the formation of a soil bank of 1.25 m high. Significant increases in SSL in the bottom slope position were also observed in previous studies. In our study region, Bork and Li (2002) reported an agricultural terrace growth of 9 m with an average increase of 0.28 m yr^{-1} over the last 3200 yr. Papendick and Miller (1977) reported that in the Palouse region of the USA, soil banks of 3 to 4 m formed as the result of tillage translocation in a few decades with an average increase between 10 and 14 cm yr^{-1}. Dabney et al. (1999) reported the development of a 0.2- to 0.25-m step across the hedges on a Loring silt loam soil near Coffeeville, MS, in just 3 yr of tilled fallow management. A much higher deposition rate in the lower field boundary in the USA than that obtained from present study in the Chinese Loess Plateau may reflect differences in sediment delivery rates as affected by overland flow, slope gradients, and tillage tool, and land management practices, etc.

The rapid increase in soil bulk density in the top slope position is due to the rapid surface soil loss and exposure of subsoil horizons. In the middle slope position, the decreasing in soil bulk density with the increase of tillage number (up to 30) reflects a loosening and soil mixing processes by tillage. The addition of subsoil from the upper slope may account for an increase in soil bulk density from 30 to 50 tillage in the middle slope. These spatial variations in bulk density induced by tillage are in agreement with the findings by Dabney et al. (1999) and Agus et al. (1997). Dabney et al. (1999) pointed that there was a trend of increased bulk density under tilled areas due to compaction possibly caused by repeated tillage, lack of root growth, and deeper exposure of subsoil horizons.

Soil redistribution by intensive tillage resulted in deterioration in soil quality within the tilled layer in the upper slope and temporary improvement in the lower slope. The rapid decline in SOM and soil nutrients in the upper position is attributable to loss of surface soil with tillage (Table 1). Thapa et al. (2001) reported a soil nutrient gradient across the terraces at Claveria, Philippines. Schumacher et al. (1999) obtained an increase in productivity index (Pierce et al., 1983) in the footslope region of a soil catena. Li and Lindstrom (2001) found a significant positive relationship between soil nutrients and soil accumulation from tillage on the steep hillslope and terraces. Soil redistribution by tillage might provide some short-term soil quality benefits in the lower slope positions as evidenced by increased SOM and available nutrients within the plowing layer. However, the continuous accumulation of soil materials above the initial surface soil by long-term intensive tillage will eventually result in the degradation of soil quality in the lower portions of the slope (Table 4). Negative linear correlations between soil quality parameters and tillage numbers for most slope positions suggests that long-term tillages will deteriorate soil quality eventually for the entire slopes.

Based on the above results, we conclude soil redistribution by intensive tillage resulted in deterioration in soil quality within the tilled layer in upper slope and temporary improvement in lower slope. As our intensive tillage was conducted in a very short duration (5 d for 50 tillage operations), caution therefore must be exercised when extrapolating the results to a real field situation as decaying roots, plant residues, and possibly soil amendment between tillages may modify the soil quality as well.

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